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STATISTICAL TROPICAL CYCLONE FORECASTING TECHNIQUES FOR THE SOUTHERN HEMISPHERE

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Statistical models for forecasting Southern Hemisphere tropical cyclones were adapted, developed and tested for use by the Joint Typhoon Warning Center, Guam. On the limited sample, it was apparent that the Australian aids used in the evaluation were able to provide better forecasts than the JTWC aids.

Operational trials of the Australian aids for at least two Southern Hemisphere tropical cyclone seasons are recommended.

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Block 20, Abstract, continued.

>This report is divided into two parts, each with its own summary and conclusions: Part 1, Evaluation of Several Australian Statistical Tropical Cyclone Forecasting Techniques for Use at Joint Typhoon Warning Center; and Part 2, Development and Testing of New Statistical Forecasting Techniques for the Southern Hemisphere.

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Part 1. Evaluation of Several Australian Statistical Tropical Cyclone Forecasting Techniques for Use at Joint Typhoon Warning Center

Abstract

Australian statistical tropical cyclone forecasting techniques were tested for use by the Joint Typhoon Warning Center (JTWC) in Guam. These aids were tested on almost identical Australian and Fleet Numerical Oceanography Center (FNOC) data during the 1982/83 Southern Hemisphere tropical cyclone season to seek potential problems. Some loss in accuracy was apparent with the "statistical-synoptic" models when using FNOC data. The forecast errors, however, were still less than the official JTWC errors for that season.

1.1 Introduction

During 1980, in support of U.S. Navy deployments in the Southern Hemisphere, the Joint Typhoon Warning Center (JTWC) at Guam began routine tropical cyclone forecasts in the Southern Hemisphere. This extension in the area of JTWC responsibility necessitated the accumulation of new forecasting skills and experience.

The derivation and evaluation of several guidance techniques of potential use to JTWC in the Southern Hemisphere are described in this report. The aims of this project were

(1) to adapt (using FNOC data) existing Australian techniques over the expanded domain required by JTWC, and

(2) to compare the performance of such techniques with a current FNOC numerical tropical cyclone model and JTWC forecasts to evaluate their operational usefulness.

The Australian schemes tested a track analogue approach and various "statistical-synoptic" models, i.e., statistical models developed with synoptic predictors derived from current synoptic analyses. "Statistical-dynamical" models developed in Australia (models that included predictors derived from numerical model prognostic fields) were not tested because of the lack of archived prognostic data at FNOC. In addition, Keenan (1984) showed that Australian statistical-dynamical models had no more skill than the statistical-synoptic models.

A test in which the models were run simultaneously on independently-obtained, equivalent Australian and FNOC data was used to evaluate the effect of the data base on their performance of the models. Finally the models were tested over the region of JTWC responsibility and compared to the official JTWC forecasts.

1.2 Description of the Australian Forecasting Techniques

The Australian techniques were developed at the Bureau of Meteorology, Australia for use in the Australian area of forecasting responsibility (80°E to 160°E). Australian data were employed in their original development.

1.2.1 The Track Analogue Technique

The track analogue technique called CYCLOGUE was developed by Annette (1978) similar to the U.S. Navy analog technique described by Brand and Belloch (1976). In each forecast, an entire history of storm tracks is searched for storms similar to the current storm. To overcome the problem of insufficient analogues in many situations, the basic acceptance criteria were enlarged by a function dependent on the normalized tropical cyclone frequencies for the time of year and 5° latitude-longitude square in which the storm was located.

The track analogues were colocated with the subject storm and adjusted to have the same initial heading. The mean of the analogue positions at each interval was then blended with a persistence forecast to obtain the CYCLOGUE forecast. This blend employed a weighting of 100% persistence at 12h, a value which

decreased to 0% at 36h; by that period the forecasts consisted entirely of the track analogue component. Probability ellipses obtained from the spread of track analogues could be obtained with the technique.

As the Australian track analogue data base for CYCLOGUE was concentrated in the Australian region, it was necessary to obtain storm tracks over the entire area of JTWC responsibility (20°E to 180°E). Storm tracks prepared by the NOAA Environmental Data Service (EDS), National Climatic Center, were used for this purpose. The EDS S.W. Indian, S.W. Pacific and Australian basin storm data bases, for the period 1900 to 1979, were combined to form one track data set for the Southern Hemisphere. This provided 1395 storms, distributed by month as in Figure 1 and geographically as in Figure 2.

1.2.2 The Classical Forecast Equations

The methods described in this section are the Australian statistical-synoptic forecast equation approaches. Equations were developed for the prediction of the eastward (X) and north-ward (Y) components of tropical cyclone motion using, as the predictors past track data, the CYCLOGUE forecasts and analysis synoptic data. Originally the forecast equations were developed for 12, 24, 36 and 48h intervals only. JTWC, however, has an operational requirement for 72h forecasts thus, the classical equations were extended for 60 and 72h forecasts. Both multiple linear regression and empirical orthogonal functions (EOF) were used to develop forecast equations.
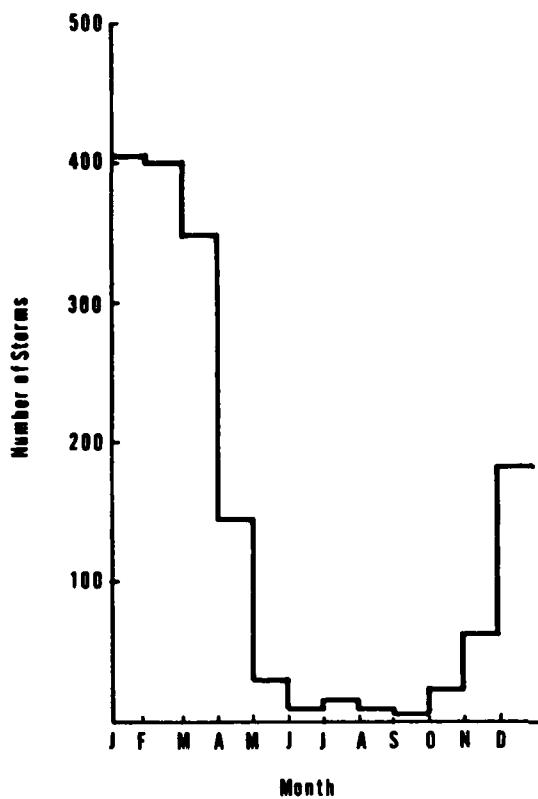
Figure 1. Number of storms
for the CYCLOGUE 1900-1979
Southern Hemisphere data
set.
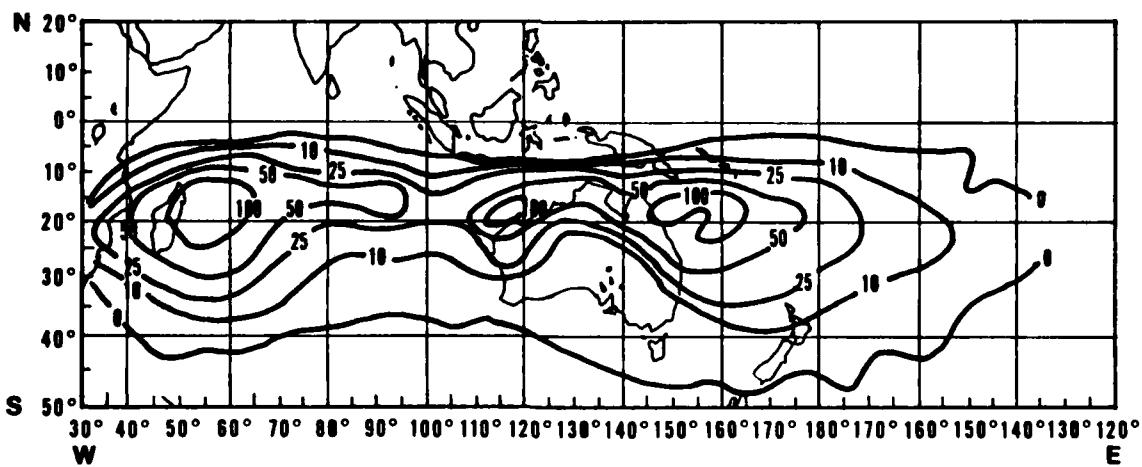
Figure 2. Number of storm positions per 5°x5^{o} square
for the CYCLOGUE 1900-1979 Southern Hemisphere data set.

The developmental data were obtained from 856 tropical cyclone situations in the Australian region of responsibility, between November 1970 and May 1980. An independent data set was formed by randomly removing 50 forecast situations. The best track data of Lourensz (1981) were used for the cyclone positions, the analogue technique CYCLOGUE provided blended track analogue and persistence forecasts. The synoptic data were derived from standard Australian region grid-point analyses (Seaman et al, 1977) archived by the Bureau of Meteorology, Australia.

To formulate the synoptic predictors, the 121 element 220 km spacing storm-referenced grid shown in Figure 3 was derived. The subfield was offset to restrict the number of tropical region grid points where the analyses were known to revert to climatology. Prescreening of subgrid D-values and past 24h height field changes at 1000, 850, 700, 500 and 300 mb was then undertaken to derive 25 synoptic potential predictors for both the X and Y directions for each forecast interval. The synoptic predictors were then combined with the analogue forecast and persistence forecast, to form a basic prediction data set from which the multiple linear regression and EOF analyses were undertaken.

The classical regression equations (CREG) were obtained by screening the final predictor data set using the UCLA Biomedical computer program, BMDP2R, described by Dixon (1981). The resulting equations were analogous to those of NHC-67 (developed by Miller et al., 1968); however, no stratifications were employed in this case.
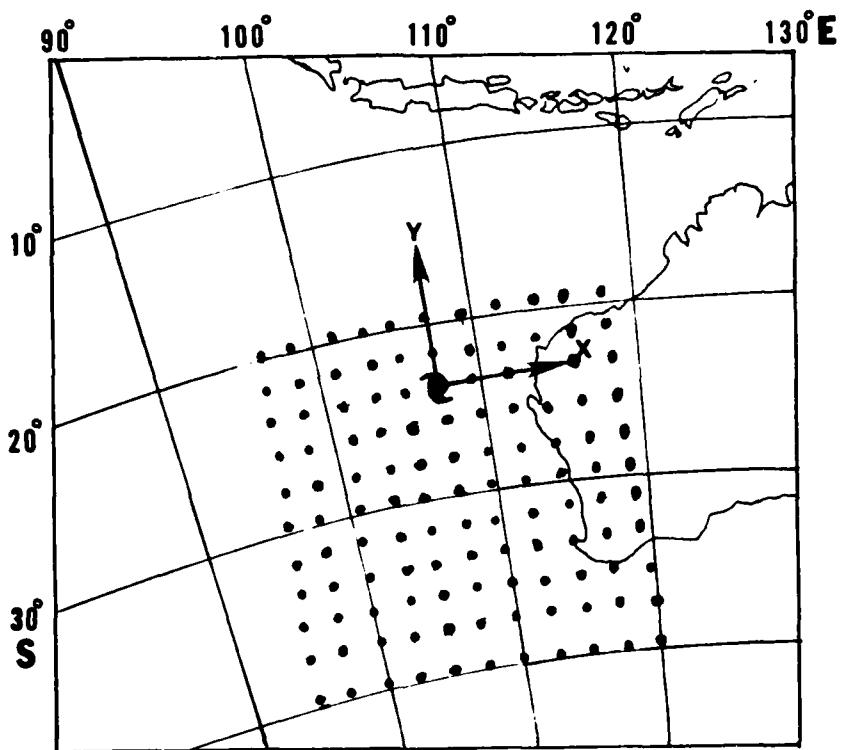
Figure 3. The 220 km spacing, 121 element
Australian storm-referenced subgrid.

The EOF analysis followed Jasperson (1972). In this method,
an EOF analysis was first undertaken on the entire final predictor/
predictant data set. Then a multiple linear regression analysis
was used to estimate the eigenvector coefficients, using only the
original potential predictors as the independent variables. These
estimated eigenvector coefficients were then used to recover the
predictant (EIGV) or forecast values of X and Y motion. In this
case, as the basic data set had previously been obtained by
prescreening, full use was not made of the EOF capability to
represent the entire synoptic component in the manner described
by Shaffer and Elsberry (1982). Again, as in the CREG approach,
no stratifications were used in the prediction scheme.

1.2.3 Discriminant Analysis Forecast Technique

The previous statistical-synoptic methods made no attempt to stratify the dependent data to obtain more homogeneous developmental data and thus, lower errors. The technique described here did use stratification, and also attempted to give additional diagnostic information on the storm's behavior. This was done by using probabilities for the occurrence of specific storm displacement ranges. It was an attempt to give extra information to the forecaster, in particular the probability of unusual or unexpected storm motion.

The approach adopted here was to use the discriminant analysis technique, in an attempt to indicate probabilities of motion type. The choice of these categories was somewhat arbitrary and could have been specific motion, e.g., the recurvature/non-recurvature study of Leftwich (1979), or storm track types. Given the more erratic behavior of many Australian storms and the problems imposed by the non-unique nature of tracks during the lifetime of each storm, it was decided to opt for a simple solution. From the distributions of X and Y motion during each forecast interval, the 33 percentile values were used to obtain three categories of motion in each direction: below average, average and above average storm displacement. Thus, the aim was for the discriminant analysis procedure to provide the probability of below average, average or above average motion in both the X and Y direction during each forecast interval. In addition, regression equations (DISCA) developed for each

category would provide position forecasts to be used with the probabilities of each motion category. Stratification in this manner, because of storm behavior, was considered an attractive alternative to those normally employed in tropical cyclone forecasting. It is a first step toward isolating unusual storm behavior.

The discriminant analysis procedure is described by Miller (1962) and Rao (1970) and, more recently, Afifi and Azen (1979). The technique uses discriminant functions of the form

$$S_j = C_o + \sum_{i=1}^{M} C_{ji} X_i$$

where j denotes the group, X_i the predictor, C_{ji} the coefficients of the discriminant functions and m, the number of predictors. This linear combination of predictors has been designed to maximize the ratios of the between group sum of squares to the within group sum of squares. The "posterior" probability P of each group is then given by:

$$P_j = q_j \exp S_j / \sum_{k=1}^{\ell} q_k \exp S_k$$

where ℓ denotes the number of groups and q_j is the "a priori" probability of group j in the original population (0.333 in this case). The category with the largest posterior probability represents the most probable outcome.

To derive the discriminant functions, 76 potential predictors were screened using the BMDP7M software package described by Dixon (1981). The potential predictors included: the storm's central pressure; latitude and longitude; the X and Y components of the CYCLOGUE forecast; PERSISTENCE forecasts (two for each component); and 61 synoptic predictors. The 61 synoptic predictors were D-values and 24h height field changes, selected by prescreening the storm referenced synoptic field data, at the levels used in the development of the CREG equations. A Monte Carlo simulation, in which groups were randomly mismatched with their predictor sets, was used to calculate the appropriate F values. Equations were only developed for forecasts out to 48h; experience indicated there was insufficient classification skill available at the longer intervals.

1.2.4 Prior Performance of the Australian Aids

The performances of the Australian aids, to 48h, as the mean vector error (mean of the great circle distances between the forecast and actual storm locations) for the dependent and independent test data sets are given in Table 1. Also included are the errors of PERSISTENCE (extrapolation with the past 12h motion) i.e., a no-skill forecast method. The errors shown were obtained with the best-track Australian storm locations of Lourensz (1981). CYCLOGUE also employed its Australian storm track data set.

Table 1. Mean Forecast Errors (km) for the Australian aids
on Australian dependent and independent data.

		Forecast Intervals			
Data Set	Technique	12	24	36	48
	CREG	87	176	280	391
Dependent	EIGV	86	167	261	364
"Best-track"	DISCA	81	173	275	375
	CYCLOGUE	91	218	357	493
	PERSISTENCE	88	203	343	499
	NUMBER OF CASES	780	687	600	523
	CREG	85	169	259	360
Independent	EIGV	83	161	257	371
"Best-track"	DISCA	83	157	276	345
	CYCLOGUE	93	226	381	524
	PERSISTENCE	86	195	336	501
	NUMBER OF CASES	50	50	50	50

The statistical-synoptic approaches produced similar
errors and were consistently better than either CYCLOGUE or
PERSISTENCE. On the independent test sample, using the null
hypothesis of no difference against the one-sided alternative
that the CREG errors were better than the PERSISTENCE errors,
the significant levels (α) were 43.6% at 12h; 25.1% at 24h; 1.9%
at 36h and 0.7% at 48h. In addition, as found by Keenan (1981),
CYCLOGUE did no better than the no-skill PERSISTENCE forecast.
In the results presented by Keenan (1984), however, CYCLOGUE was
competitive (in an operational mode) with PERSISTENCE at the
longer intervals where the storm locations were less well known.

The DISCA classification accuracy at the 24h interval is given in Table 2, for both the dependent and independent data sets, as contingency tables. For the dependent data 75% of the X cases were correctly classified, while this figure decreased to 60% in the Y direction. This was a reflection of the relative difficulty that statistical schemes have consistently shown in forecasting the Y component of cyclone motion (Neumann and Hope 1973; Keenan 1982). For the independent data, 80% in the X direction and 58% in the Y direction were correctly assigned.

Table 2. Contingency tables for the 24h forecast interval shows the predicted vs. actual below average (S), average (M), and above average (L) motion categories in the X and Y directions. Also given are the percentage of correct classifications (PC) and the Brier Skill Scores (BS).

Data Set		X Direction						Y Direction			
		Discriminant Forecast						Discriminant Forecast			
		S	M	L	Total			S	M	L	Total
Dependent	S	162	40	3	205	Actual	S	132	52	14	198
Actual Data Group	M	41	173	33	247	Group	M	48	107	56	211
	L	8	47	180	235		L	31	72	175	278
		211	260	216	687			211	231	245	687
		PC = 75.0	BS = .364					PC = 60.2	BS = .509		
		Discriminant Forecast						Discriminant Forecast			
		S	M	L	Total			S	M	L	Total
Independent	S	15	2	0	17	Actual	S	10	4	2	16
Actual Data Group	M	3	5	3	11	Group	M	7	9	4	20
	L	0	2	20	22		L	1	3	10	14
		18	9	23	50			18	16	16	50
		PC = 80.0	BS = .302					PC = 58.0	BS = .550		

At 48h the respective dependent and independent values were 59% and 64% in the X direction, and 57% and 48% in the Y direction. By way of comparison, a no-skill process would yield a 33% value. In the individual categories, the two extreme groups were always better classified than the average group. At 24h, with the independent sample in the more difficult Y direction, only 13% of below average cases were classified as above average and only 7% of the above average cases were assigned to the below average group. In the X direction where many storm accelerations are reflected, less than 4% of these misclassifications between the extreme groups were found. This ability to distinguish extremes is potentially an important aid to the forecaster.

The reliability of the posterior probabilities for the dependent data set, at 24h, is shown in Figure 4. Insufficient cases were available for such an analysis of the independent data set. In general the agreement was good. The large deviation from the expected values in the below average Y group was a consequence of only 9 cases in that probability range. The lack of high probabilities in the X and Y average groups were caused by the higher proportion of misclassifications discussed previously. This is of course, a weakness in the technique. However, below average to average and average to above average group misclassifications are not as serious as misclassifications between the two extreme groups.
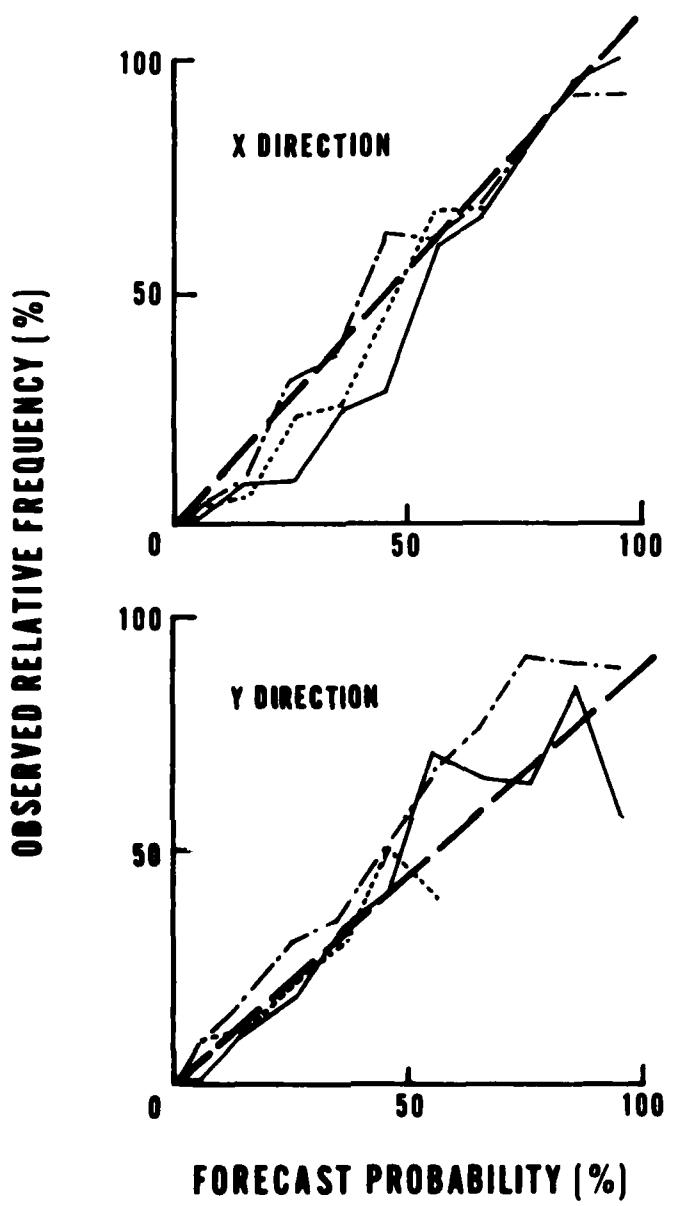
Figure 4. Reliability of the DISCA posterior probabilities for the below average (————), average (————), and above average (—·—) groups at the 24 hour interval, on the dependent Australian data.

1.3. Performance of the Australian Aids on FNOC Data

JTWC Southern Hemisphere forecast errors for the years
1980-83 averaged 272 km at 24h and 515 km at 48h. Because of the
smaller Australian and forecast errors, it was decided to test
their operational usefulness with FNOC data. Such a transfer,
while conceptually simple, could potentially introduce serious
flaws in the application of statistical schemes. The difference
between Australian (Seaman et al., 1977) and FNOC (Barker, 1982)
analysis schemes, the representation of the storms within the
analysis, and the positioning of the storms all could contribute
to serious data base inhomogeneities. A similar problem was
cited by Neumann (1979): It happened at National Hurricane Center
when the original National Meteorological Center (NMC) scan
analysis method (Cressman, 1959) was replaced by the first-
guess/spectral analysis/ primitive equation hemispheric
prognosis package. The changes in the tropical analysis error
characteristics resulted in substantial deterioration in the
performance of their statistical-synoptic and statistical-
dynamical guidance models, particularly NHC-73.

1.3.1 A Homogeneous Comparison of the Australian Forecast
       Methods on FNOC and Australian Data

Before attempting to use the Australian aids, it was
necessary to determine the degradation in performance that would
result from their use of FNOC data. Thus parallel runs of the
statistical-synoptic models were undertaken with Australian and
FNOC data sources.

This experiment was undertaken with 1982/83 Southern Hemisphere tropical cyclones. The following two data sets were used to produce parallel sets of the statistical-synoptic forecasts:

(1) Bureau of Meteorology, Australia, 11 GMT and 23 GMT operational tropical cyclone positions and grid-point analysis data.

(2) JTWC operational 12 GMT and 00 GMT storm positions and FNOC southern hemisphere grid-point data.

The latter fields were derived by interpolation from the Navy Operational Global Atmospheric Prediction System (NOGAPS) global analysis fields. No attempt was made to alter the one hour difference in forecast times. As the Australian region of forecast responsibility is smaller than JTWC, only forecasts for Australian region storms were compared. This was consistent with the original development of the equations and provided an additional independent test for validity. In addition, it removed the problem of variance induced by use of the techniques in regions where they were not developed.

The results of this comparison are shown in Table 3. In addition, results obtained when linearly combining the three DISCA forecasts are shown. Here the posterior probabilities for each motion category were used to form a weighted combination (DISCW) of the individual category regression forecasts. This combination forecast could be described as a type of "hedging" forecast. In addition, because of the JTWC requirement, the CREG and EIGV results to 72h were included.

Table 3. Homogeneous comparison of the Australian "statistical-synoptic" forecast errors (km) obtained with Australian and FNOC data for the 1982/83 Southern Hemisphere tropical cyclone season.

| Data Set | Technique | Forecast Interval (h) | | | | | |
		12	24	36	48	60	72
	CREG	101	180	275	390	509	631
	EIGV	147	250	351	459	546	642
Australian	DISCA	117	200	299	452	---	---
	DISCW	101	176	272	410	---	---
	CREG	122	211	299	401	526	669
	EIGV	117	332	445	458	560	675
FNOC	DISCA	133	222	306	431	---	---
	DISCW	126	213	285	397	---	---
Number of Forecasts		48	42	38	34	31	29

With the Australian data, the CREG and DISCW techniques produced errors close to those of Table 1. While acceptable, the DISCA values were larger and the EIGV values were exceedingly large. The reason for the EIGV failure was not clear and warrants further investigation. When the FNOC data was used, the average changes from the Australian data base errors were 9.7% at 12h, 20.5% at 24h, 10.6% at 36h, -1.3% at 48h, 2.9% at 60h and 5.6% at 72h. Significance level values (α) values for the differences between the CREG errors on Australian and FNOC data were; 12.3% at 12h, 14.2% at 24h, 29.5% at 36h, 36.7% at 48h, 42.5% at 60h and 33.4% at 72h. Despite the relatively small number of cases,

it was apparent that the statistical-synoptic models performed less satisfactorily on the FNOC data. It was encouraging, however, to find the significance of the changes smallest at the longer intervals where many key decisions must be started in U.S. Navy users.

Reasons for the error increases are varied. For the tropical cyclone positions alone, the mean vector difference between the JTWC and Australian estimates was 76.4 km. In addition, the mean FNOC storm sub-field characteristics were different from the Australian developmental data set as shown in Figure 5. In the FNOC data, the mean storm was not as intense at 500 mb; however, the surrounding height field was higher resulting in the stronger height gradient south of the storm. Also, the FNOC X correlations were weaker, while its Y correlations were larger.

The exact role these differences played in the manifestation of the larger errors was difficult to ascertain without a more thorough analysis. To some extent, the lower latitude of the 1982/83 sample may have contributed to the synoptic differences. However, differences did exist and the result was a less satisfactory performance of the Australian statistical-synoptic models when using FNOC data.

1.3.2 Performance of the Australian Aids over the Entire Region of-JTWC Responsibility

As the JTWC forecasting area extends much further than the Australian region, it was important to establish that the techniques could be used over this wider area. The forecast errors of the Australian techniques using FNOC data, for all attainable

MEAN 500 MB AUSTRALIAN HEIGHT FIELD

MEAN 500 MB FNOC HEIGHT FIELD

ZONAL CORRELATION

ZONAL CORRELATION
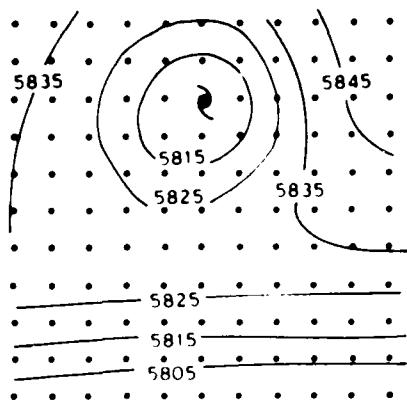
MERIDIONAL CORRELATION
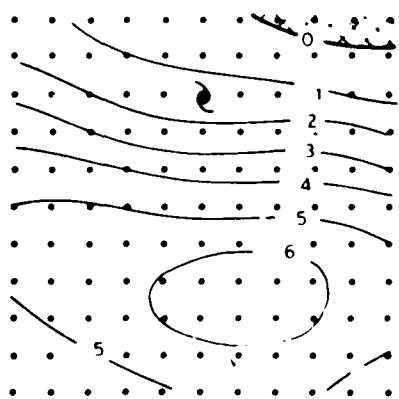
MERIDIONAL CORRELATION

a

b
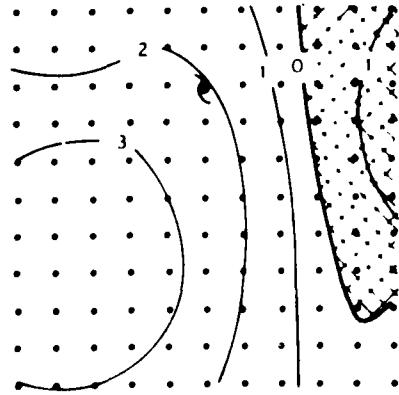
24 HR DATA - STORM MEANS

Latitude 18°S
Longitude 133°E
24 hr zonal mvt 45 km
24 hr meridional mvt 167 km
Central pressure 981 mb
Number 759
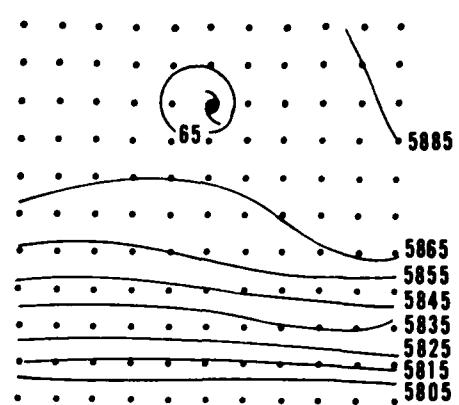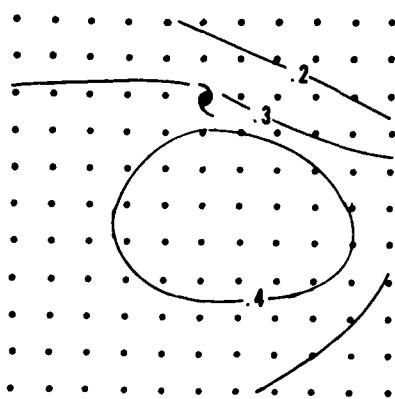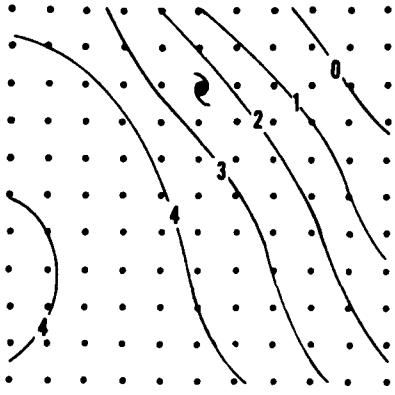
24 HR DATA - STORM MEANS

Latitude 17°S
Longitude 136°E
24 hr zonal mvt 25 km
24 hr meridional mvt 193 km
Central pressure 986 mb
Number 124

Figure 5. Mean characteristics of the 220x220 km storm-referenced
subgrid at 500 mb for the Australian developmental data set (a)
and the 1982/83 FNOC data set (b) at the 24 hour forecast interval.
X correlations are positive for storm motion to the east and Y
correlations are positive for storm motion to the north.

1-19

forecast situations during the 1982/83 season, are therefore presented in Table 4. Again the forecasts were verified against the original operational tracks. Also included are the official JTWC 24h and 48h forecast errors and the errors of the Navy Nested Tropical Cyclone Model (NTCM) (Harrison, 1973, 1981).

Table 4. Comparison of the Australian aids, the official JTWC forecasts and NTCM forecast errors (km), and standard deviations (km) for the 1982/83 season obtained over the entire region of JTWC responsibility during the 1982/83 Southern Hemisphere tropical cyclone season.

Forecast Errors:

			Forecast Intervals (h)			
Technique	12	24	36	48	60	72
CREG	121	207	294	398	541	689
EIGV	163	274	369	468	590	720
DISCA	131	219	303	427	---	---
DISCW	125	206	285	396	---	---
CYCLOGUE	126	227	331	423	534	675
Number of Cases	112	95	78	67	59	53
JTWC	---	241	---	446	---	---
Number of Cases	---	163	---	126	---	---
NTCM	128	265	383	547	701	785
Number of Cases	43	33	28	21	19	17

Standard Deviations:

	12	24	36	48	60	72
CREG	89	133	193	256	348	489
EIGV	90	137	202	274	379	482
DISCA	89	119	169	230	---	---
DISCW	90	123	175	230	---	---
CYCLOGUE	93	137	198	247	331	413
Number of Cases	112	95	78	67	59	53
JTWC	Not available					
NTCM	Not available					

The latter model is a three layer, primitive equation model with a moving, two-way interactive fine mesh grid embedded within a coarse grid. The NTCM is initialized from the FNOC global band analysis. It should be noted that the NTCM used the analysis previous to that of the other statistical methods, in the manner of its operational use. For various reasons, it was not practical to obtain a sufficiently large homogeneous sample in Table 4.

The Australian "statistical-synoptic" errors (except for EIGV) were only slightly changed and were not, in the statistical sense, significantly different from the previous values given in Table 3. The CREG and DISCW performed best overall, at least to 48h where CYCLOGUE was marginally superior. The lack of a large error increase indicated that the equations were still robust when used out of their developmental region. The use of D-values in the synoptic forcing may have generalized the equations for this application.

Although care should be taken in comparing the non-homogeneous JTWC and NTCM errors, it was apparent that with the EIGV exception, all Australian aids were superior. Compared to the official JTWC results, the CREG values were 14% lower at 24h and 11% lower at 48h. To test the statistical significance of these differences it was assumed that the JTWC errors had a standard deviation of 140km at 24h and 240km at 48h. These values were consistent with the range given in Table 4. With these assumptions, the α values for the differences between CREG and JTWC forecasts were 3% at 24h and 10% at 48h. Although

both α values did not meet the normally accepted 5% level, they did indicate that the CREG results were worth further operational consideration. Similar conclusions apply to the DISCW approach. It should be mentioned that the NTCM errors were larger than those presented by Peak and Elsberry (1982), where a larger sample was tested. They also obtained slightly better errors than the CREG technique when they applied statistical post-processing to the NTCM. However they did not use operational storm locations as employed in this study.

1.4 Summary and Conclusions, Part 1

The tests of the Australian aids provided additional evaluation of their performance. With an Australian data base on Australian storms, except for EIGV, there was no major change from their previously found forecast performance. When JTWC track data and FNOC synoptic grid-point data were used on the same set of forecast situations, there was an overall decrease in the forecast accuracy. Averaging the CREG, DISCA and DISCW results, the maximum change in forecast error due to different data sets was 19.6% at 12h. At the longer intervals (>48h), however, the percentage change averaged over all the tested techniques (except EIGV) was only 2.3%. Thus the statistical-synoptic forecast schemes did suffer some degradation in performance when FNOC data was used, but the deterioration was most apparent at the shorter forecast intervals.

When the Australian statistical-synoptic models were
applied over the entire JTWC region, i.e., areas outside their
original development area, there was no major change from the
errors obtained with FNOC data in the Australian region. In fact
most errors were slightly smaller. This indicated that the
Australian schemes were robust over the entire region required
by JTWC. With the exception of EIGV, all the Australian
statistical-synoptic models exhibited similar accuracy and
were better than any of the alternatives including the JTWC
forecasts. For the 48h to 72h forecasts, the track analogue
technique produced better errors. The differences, however, were
not statistically significant.

The performance of the Australian aids, except for the EIGV
technique, warrants further investigation. The test samples used
in this report were relatively small; however, since the CREG
and DISCW techniques produced lower errors than JTWC indicates,
they should be used for a more complete operational trial.
CYCLOGUE should also be included as it produced compet'tive
long term (60h-72h period) errors. Future work should also be
directed to developing statistical techniques with the FNOC data
base along the lines described in Part 2 of this report.

Part 2:   Development and Testing of New Statistical Forecasting Techniques for the Southern Hemisphere

Abstract

The global band wind field grid-point data was used to develop statistical-synoptic tropical cyclone forecast schemes for the Southern Hemisphere. Coordinate systems aligned geographically and along the past direction of tropical cyclone motion were compared. Stratifications on the basis of the geographical location of the storm and its position relative to the subtropical ridge were also tested on both coordinate systems. Best results were achieved, especially in the operational environment, with non-stratified, non-rotated forecast equations. In comparison to previous techniques that used height field data for the synoptic component, the use of the global band wind field data did not seem to produce any significant effect on the forecast errors.

2.1 Introduction

The techniques evaluated in Part 1 were primarily developed for the Australian region using Australian data sources. It was shown that some degradation resulted from using them with the non-Australian data as well as over the wider JTWC domain. The implication was that the different statistical characteristics of the FNOC data source resulted in the less satisfactory performance of the statistical-synoptic models. This does not mean that the FNOC data was worse, just that it had different statistical characteristics from the original developmental data. It was therefore appropriate to test statistical models developed with FNOC data.

To facilitate the development of a statistical model with the FNOC data base, the global band analysis scheme described by Grayson (1971) and Lewis (1972) was selected. This data set consisted of numerical surface pressure and various upper wind analyses in a global band from 41°S to 60°N. The attractive feature was the relatively long and consistent data archive since 1974. As it was essentially a tropical wind analysis scheme, it also provided a method of using wind rather than mass fields as the synoptic component in statistical prediction schemes. All previous "statistical-synoptic" models described in the literature (Miller et al., 1968; Neumann et al., 1972; Leftwich and Neumann, 1977; Neumann and Lawrence, 1975) used mass fields for the synoptic component.

2.2 The Developmental Data Bases

The 1974-81 period of global band archive determined the storms used in this diagnostic study. Since 1981, the NOGAPS wind fields have replaced the global band analysis in the archive. However the global band analysis is still available in the operational mode and is used to initialize the NTCM model.

Two coordinate systems were used in the development of predictive data bases:

(1) The NAT coordinate system in which the X and Y axes were aligned positive eastward and positive northward.

(2) The ROT coordinate system in which the axes were aligned positive to the right of the past 12h motion (X') and positive along the direction of the past 12h motion (Y'). These coordinate systems were used by Frank (1976) in composite studies of tropical cyclones and more recently by Shapiro and Neumann (1984). In the latter, it was found that reorientation-orientation of the coordinate system reduced the total 24h variance in Atlantic storm motion by 40% and made the X', Y' components almost independent. There two factors are potentially important in statistical forecast schemes.

2.2.1 The Tropical Cyclone Track Data

The Southern Hemisphere tropical cyclone developmental track data were derived from the Environmental Data Service (EDS), National Climatic Center archived data. The storm tracks were subjected to some quality control and then combined to form a 1974 to 1981 Southern Hemisphere data set of 231 storms. Tropical cyclone positions were derived every 6h, by interpolation and then storm displacements over the past 24h, 12h and forward in time in 12h increments, to 72h were calculated for every storm date. These displacements were calculated in the ROT and NAT coordinate systems. Only forecasts to 48h will be considered here.

The mean track data characteristics in both coordinate systems are given in Table 5. In the NAT system, the mean storm motion was consistently to the SSW while in the ROT system it was concentrated along the Y' axis. The NAT component correlations ranged from .2 to .3 while in the ROT system they were <.02 in magnitude. The motion variability was also greater in the NAT system, e.g., at 24h the total variance in the ROT system was 44% of the NAT value, and at 48h it was 33% less than the NAT value. These findings were consistent with those of Shapiro and

Table 5. Mean tropical cyclone motion characteristics for the 1974-81 FNOC developmental data base. Storm displacements are in km.

FORECAST INTERVAL	MEAN LONGITUDE (°E) S.D. LONGITUDE	MEAN LATITUDE (°S) S.D. LATITUDE	NAT			ROT			Number of Cases
			$\bar{x}$ σ_x	$\bar{y}$ σ_y	γxy	$\bar{x'}$ $\sigma_{x'}$	$\bar{y'}$ $\sigma_{y'}$	$\gamma x'y'$	
12	16.2 4.3	108.8 47.9	-24.3 170.7	-80.2 99.7	-.237	0.6 76.5	163.2 115.9	.012	2488
24	16.0 4.3	108.5 48.0	-45.5 330.2	-166.9 191.7	-.269	-3.1 169.5	304.8 228.6	-.005	2355
36	15.9 4.2	108.3 48.3	-65.0 481.6	-253.4 274.6	-.294	-10.7 276.1	423.6 337.1	-.019	2201
48	15.7 4.2	107.8 47.9	-85.9 624.8	-336.8 346.8	-.316	-23.3 386.2	521.0 442.4	-.019	2037

Neumann (1984) although, unlike the Atlantic region, the rotation still had a significant impact on the 48h ROT variance. The relatively low latitude of the Southern Hemisphere storms was also evident as the mean latitudes ranged from 16.2°S at 12h, to only 15.7°S at 48h.

2.2.2 Synoptic Grid Point Data

The storm referenced subgrid (Figure 6) was used to derive the wind fields relative to the tropical cyclones. In the NAT system the X-Y axes were aligned positive east and positive north, respectively. In the ROT system the Y' axis was aligned along the past 12h direction of storm motion and the X' axis positive to the right of the past 12h direction of motion. The grid points were derived on great circles with a 240 km spacing.

Using the global band analysis two wind components were derived by interpolation at the standard MSL, 700 mb, 400 mb and 250 mb levels. They were the u(u') and v(v') components in the NAT (ROT) coordinate systems. The sign conventions were as previously. As the global band analysis only extended to ~40°S, many higher latitude storms could not be treated.
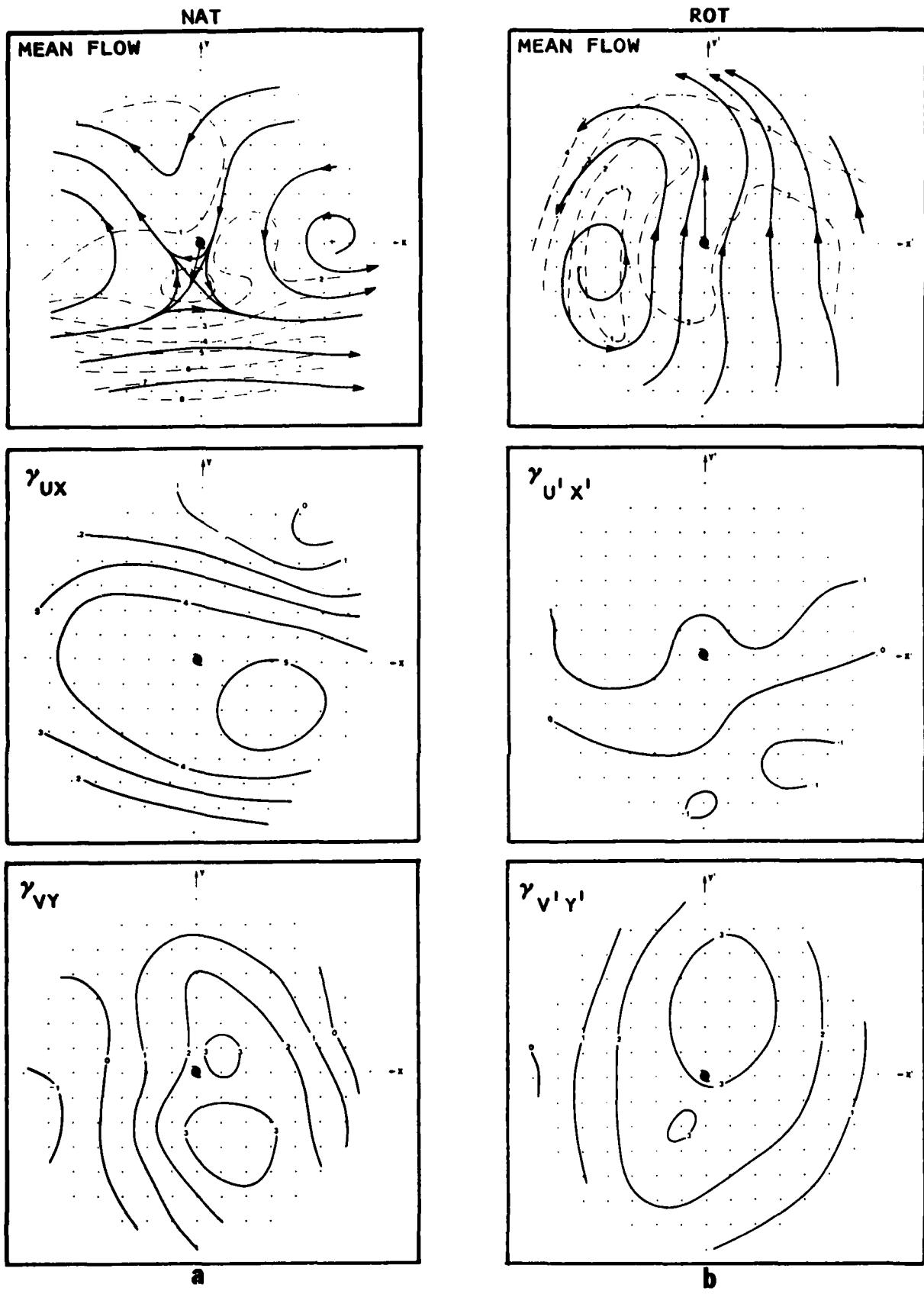
Figure 6. The 240 km storm-centered subgrid used to derive synoptic predictors for the FNOC Global Band statistical prediction scheme. The mean mass weighted 700, 400, and 250 mb flow in the NAT (a) and the ROT (b) coordinate systems at 24 hours is shown. Wind component correlations of u (u') with x (x') and v (v') with y (y') are given.

The mean flow and correlations with storm motion in the storm centered subgrid, for the 24h developmental data sets, are shown in Figure 6. The flow was obtained by a mass weighted combination of the 700 mb, 400 mb and 250 mb levels. The mean storm displacements in each coordinate system have also been indicated.

From the average NAT coordinate system flow, it was obvious that the mean storm position in the developmental data set was very close to the climatological position of the subtropical ridge. This was consistent with the variable nature of many Southern Hemisphere storms, especially off Eastern Australia. The correlation of u with the X motion was positive for a wide area surrounding the storm, with a maximum value ~950 km SE of the storm. The v-Y correlation was also positive to about 1000 km from the storm. The maximum values of the correlation coefficients were about the same as the mass field data values shown in Part 1.

In the ROT coordinate system, the mean field had a much more straightforward relationship to the storm motion. The horizontal shear of the subtropical ridge was not apparent close to the storm, although the anticyclone ~800 km to the left did reflect its presence, as did the large scale anticyclonic circulation in which the storm was embedded. The u' and v' correlations with X' and Y' were much weaker than the NAT correlations, especially in the cross-track direction. Note the storm circulation was not apparent in either coordinate system.

The previous results showed that the global band subfield data did exhibit characteristics consistent with storm behavior in the Southern Hemisphere. On an individual basis, however, the relatively low correlation coefficients indicated a considerable degree of uncertainty in their ability to define a steering current, especially for the cross-track direction. This spread is shown in Figure 7, where NAT steering currents are plotted in four quadrants. The steering was defined by averaging the mass weight flow over all grid points within 480 km and 720 km of the storm. Despite the variability, the distributions indicated there was some predictive information in the global band synoptic data.

2.3 The Regression Equations

Regression equations for the prediction of tropical cyclone movement over 12h, 24h, 36h and 48h were developed using the UCLA Biomedical computer program, BMDP2R, described by Dixon (1931). Component equations were developed in each coordinate system by screening 86 potential predictors. The potential predictors included the past 12h and 24h motion for both components: the storm latitude, and the storm longitude and 80 synoptic predictors. These synoptic potential predictors were every second subgrid value of the mass weighted flow in the component equation's direction. For the first set, all cases were used to derive the combined or COM equations. In the NAT system they were called COMNAT and for the ROT system COMROT equations. These equations were the simplest approach used to obtain the forecasts.
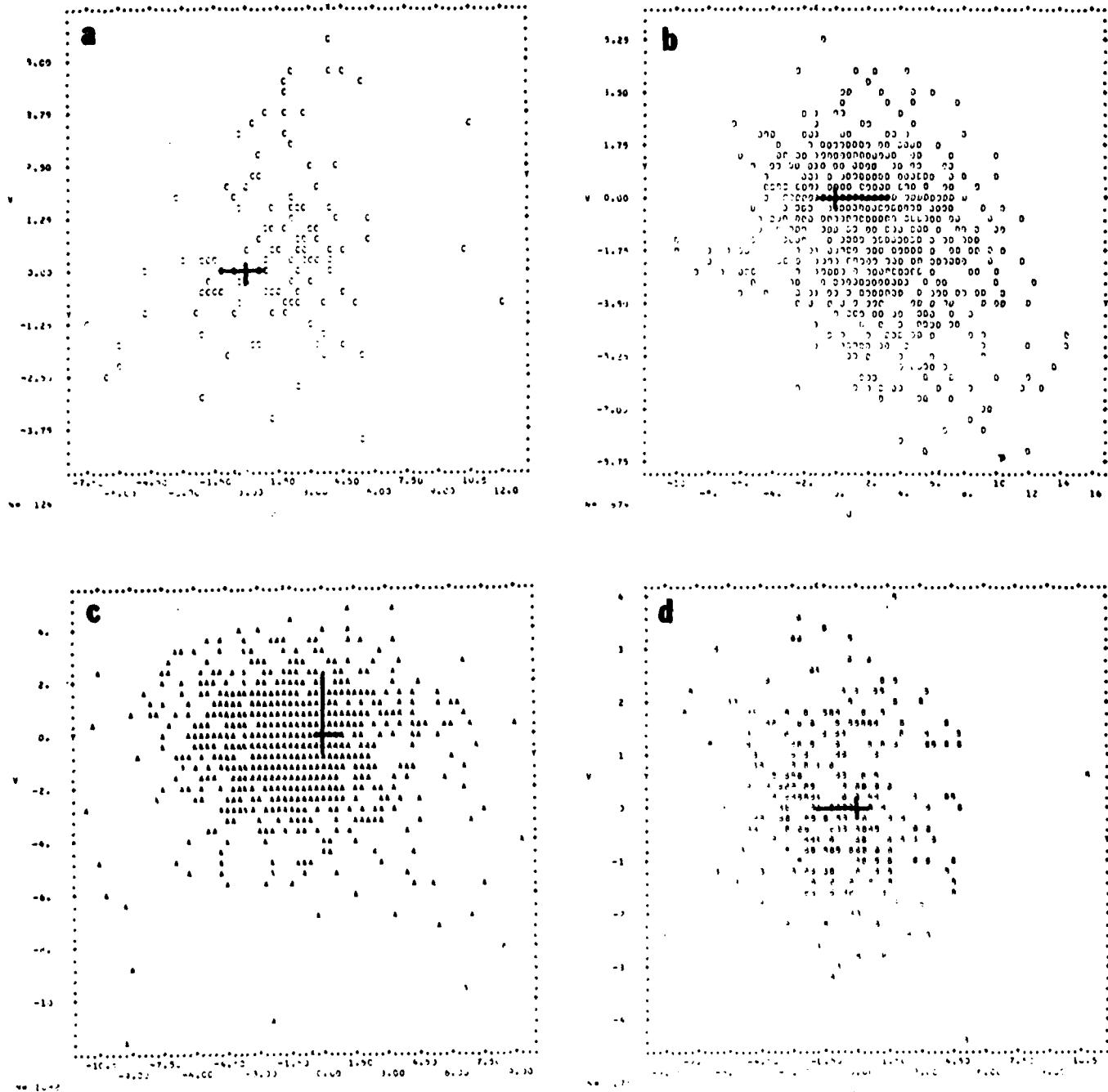
Figure 7. Distributions of global band field steering currents for tropical cyclones moving between 0-90° (a), 90-180° (b), 180-270° (c), and 270-360° (d) from north over the 24 hour forecast interval.

Southern Hemisphere storm tracks exhibit significant
regional variations as shown in Figure 8. In the southwest
Pacific, easterly motion and erratic motion are extremely common.
Off the northwest coast of Australia, westerly and southwesterly
motion are more common with many storms tracking parallel to the
Australian coast. In the mid to western Indian ocean, storms
generally track west to southwest recurving at higher latitudes
(~20°S). Regression equations were therefore developed for the
three geographical regions of Table 6, using the previous set of
potential predictors. They were labelled with the prefix GEO and
were called GEONAT in the NAT system and GEOROT in the ROT system.

Table 6. Mean tropical cyclone motion characteristics for
the 1974-81 24hr developmental data set in the various
geographical regions.

|			GEONAT		GEOROT		
REGION	MEAN LATITUDE (°S)	MEAN LONGITUDE (°E)	$\overline{x}$ σ_x (km)	$\overline{y}$ σ_y (km)	$\overline{x}'$ $\sigma_{x'}$ (km)	$\overline{y}'$ $\sigma_{y'}$ (km)	Number of Cases
0-90°E	16.1	62.3	-131.9 287.3	-148.4 181.3	-11.2 157.7	295.9 203.0	963
90-135°E	15.4	109.8	-126.1 262.9	-154.6 170.7	16.0 190.4	347.3 268.8	739
135-180°E	17.0	165.7	110.8 362.1	-207.7 215.8	-17.8 156.3	263.2 207.5	453

2-10
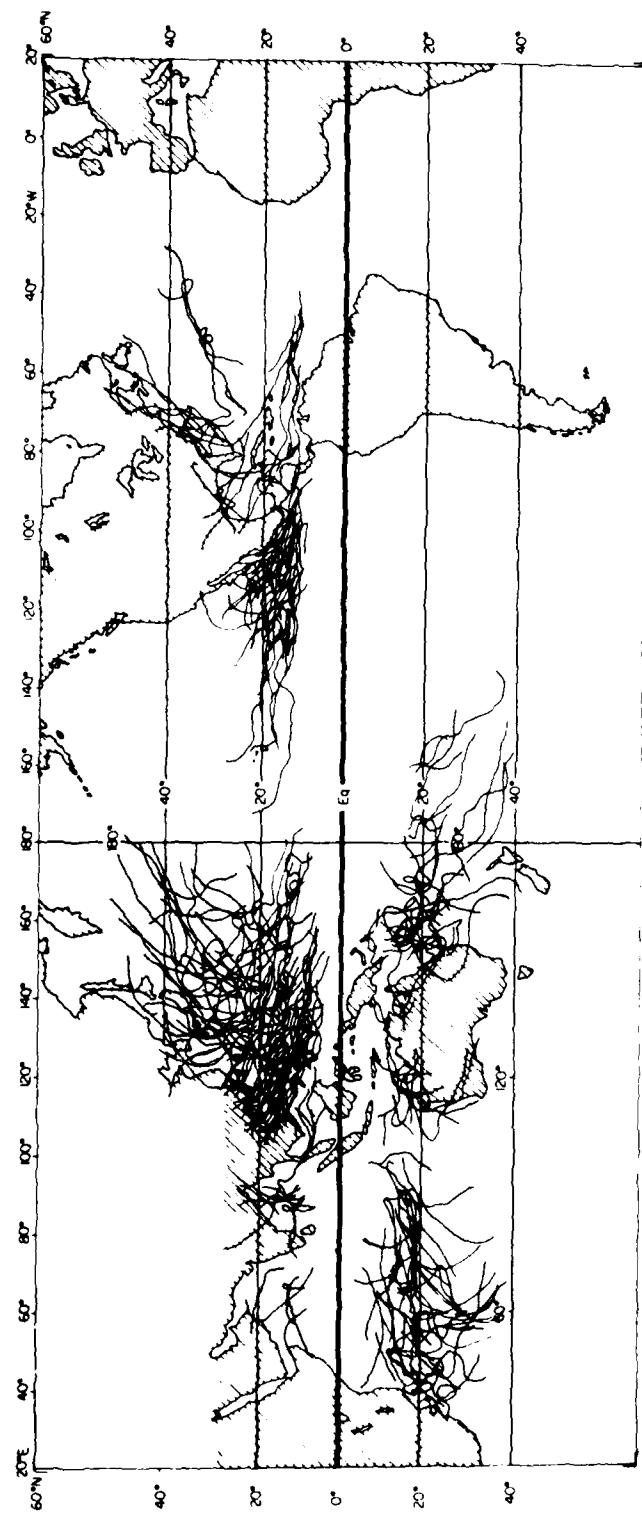
Figure 8. Tracks of tropical cyclones for a three-year period (from Gray, 1978).

In the mean, as indicated by Table 6 and Figure 8, the southwest Pacific (135-180°E) region equations had the most variable storm motion to explain. Here the predictand X and Y predictand standard deviations were larger than in the other geographical region and the mean storm motion was to the southeast, not the southwest.

Apart from the regional differences, the tracks also showed a latitude dependence. Westward motion occurred more frequently at low latitudes while eastward and southwesterly motion occurred at the higher latitudes, although there were regional differences in the exact latitudes (e.g., easterly motion occurred at a low latitude in the southwest Pacific). This latitudinal dependence can be explained partly by the monthly mean position of the subtropical ridge shown in Figure 9. Low latitude storms were north of the subtropical ridge and tended to track westward. Higher latitude storms had passed through the subtropical ridge and tracked eastward in the westerly flow. The regional differences can also be interpreted in the slant of the subtropical ridge. Xu and Gray (1982) have previously emphasized the importance of the storm's location relative to the subtropical ridge in defining tropical cyclone motion.

In an attempt to incorporate this effect in the development of the regression equations, all storm locations were stratified as being north, south or on the subtropical ridge using the following criteria:
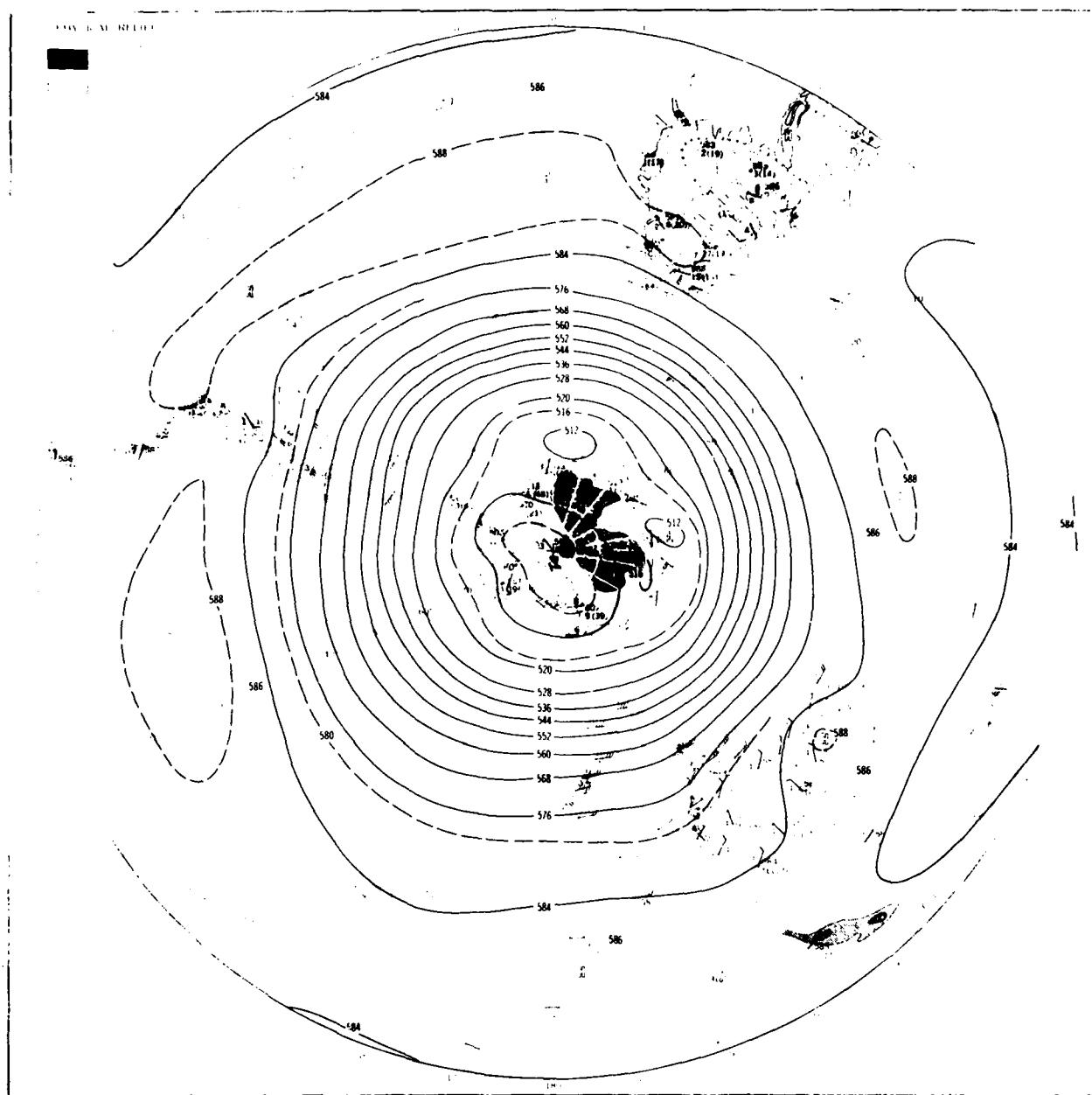
Figure 9. January monthly mean 500 mb height analysis for the Indian and southwest Pacific Oceans (from Taljaard, et al., 1969).

(1) Storm positions, where the NAT steering current speed was <1.5 m/s, were considered to be on the subtropical ridge (OSTR).

(2) Storm positions, where the NAT steering current speed was >1.5m/s and the NAT steering current had a westerly component, were considered south of the subtropical ridge (SSTR).

(3) Storm positions as in (2), but with an easterly component NAT steering current, were considered north of the subtropical ridge (NSTR).

The steering current was defined, as in the previous section, using the area averaged mass-weighted subfield flow.

Mean track characteristics for these three stratifications are presented in Table 7 while the mean subfield flows are shown in Figure 10. The simple classification appeared to capture the subtropical ridge dependence as hoped. In the main NSTR storms had a lower latitude, were north of the subtropical ridge, and had direction of motion toward the southwest. The OSTR storm cases were on the subtropical ridge with a greater degree of flow variability. The SSTR storm cases were, on the average, south of the subtropical ridge, embedded in a westerly trough, with a mean motion vector toward the southeast. The NSTR cases moved to the left of the mean environmental flow while the higher latitude SSTR storms moved to the right of the flow. These directional deviations agreed with those presented by Brand et al. (1981) and Holland (1983). In the ROT coordinate system there was little difference in the NSTR and SSTR flow, although the higher speeds in the SSTR pattern reflected the stronger westerly flow. The ROT OSTR flow was complicated but consistent with the subtropical ridge location of the data set.
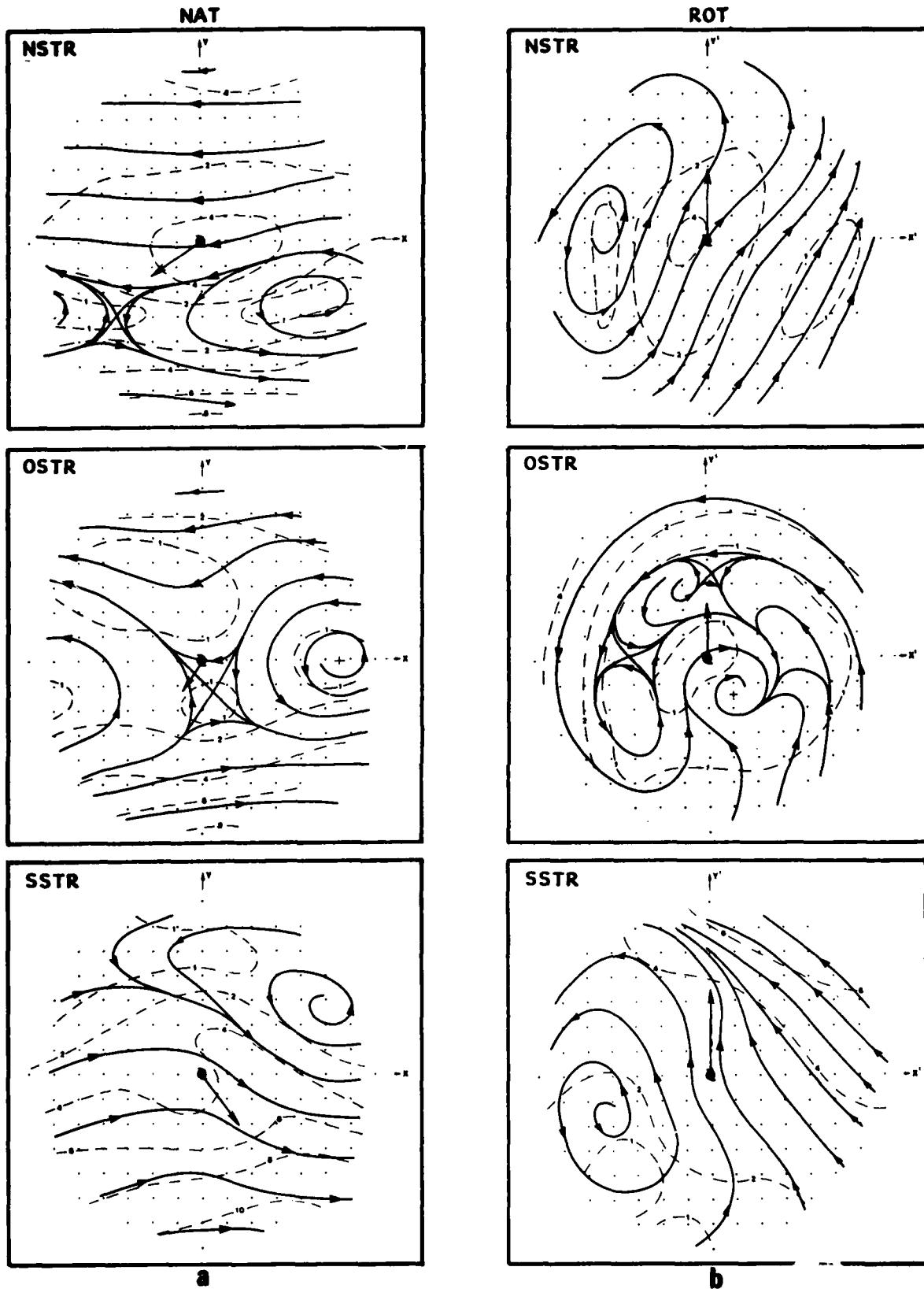
Figure 10. Mean mass weighted sub-field flows for storms classified
as north (NSTR), south (SSTR), and on the subtropical ridge (OSTR)
for the NAT (a) and ROT (b) coordinate systems for the 24 hour
developmental data set. Mean storm displacement vectors for each
coordinate system are indicated.

Table 7. Mean storm motion characteristics for the 1974-81 24h
development data to storms classified as north, south and on
the subtropical ridge.

			NAT		ROT		
STORM CLASSIFI- CATION	MEAN LATITUDE (°S)	MEAN LONGITUDE (°E)	$\overline{x}$ σ_x	$\overline{y}$ σ_y	$\overline{x}'$ $\sigma_{x'}$	$\overline{y}'$ $\sigma_{y'}$	Number of Cases
NSTR	14.2	101.0	-217.2 239.5	-144.3 153.5	-6.5 155.7	292.1 198.0	997
OSTR	14.9	101.8	-90.0 248.9	-124.7 171.3	-18.4 147.7	232.6 200.0	387
SSTR	18.4	119.0	148.2 335.1	-206.9 224.6	5.6 189.7	349.9 261.0	972

Thus, in addition to the COM and GEO equations, subtropical
or STR regression equations were developed in both the NAT and
ROT coordinate systems. Forecasts were then obtained for each
group. In the geographical stratification, forecasts from
neighboring zones were weighted within 5° longitude of a boundary
to form the forecast. This method is illustrated in Figure 11.

$$\text{GEOGRAPHIC FORECAST} = F_1 w_1 + F_2 w_2$$
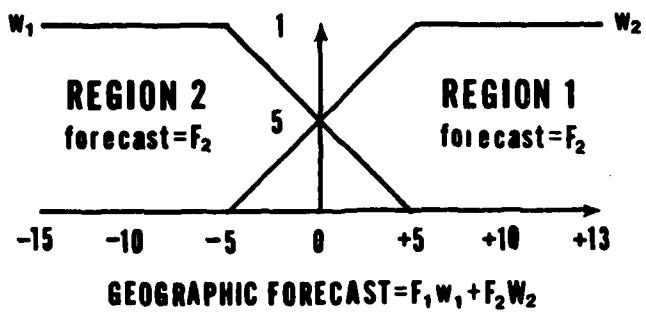
Figure 11. Method of forming the geographical the
geographical equation forecast within + or - 5°
longitude of two regions.

Individual equations will not be examined here, however it was considered instructive to consider the sources of variance reduction (RV) in the equations. The RV is defined by the relation:

$$RV = \frac{(1-SE)^2}{(SD)^2}$$

where SE is the standard error of the estimate and SD is the standard deviation of the predictand. Results from the COM equations are shown in Figure 12. Similar conclusions pertain to the other stratifications.

In the NAT coordinate system the Y component was the hardest to forecast, while in the ROT system very little RV was achieved in the X' direction. With the exception of X', the past track or non-synoptic predictors were the most important source of predictive information; however, the synoptic contribution to the RV increased at the longer intervals. These results were consistent with those found by Neumann and Hope (1973), Keenan (1982), and Shapiro and Neumann (1984) when using mass fields to derive the synoptic forcing. The small synoptic component RV was expected because the correlation coefficients, shown in Figure 6, were relatively small. Forecast equations were only derived to 48h. Figure 12 shows insufficient RV was achieved at 48h, especially in the X' direction, to expect meaningful longer term forecasts.

REDUCTION OF VARIANCE
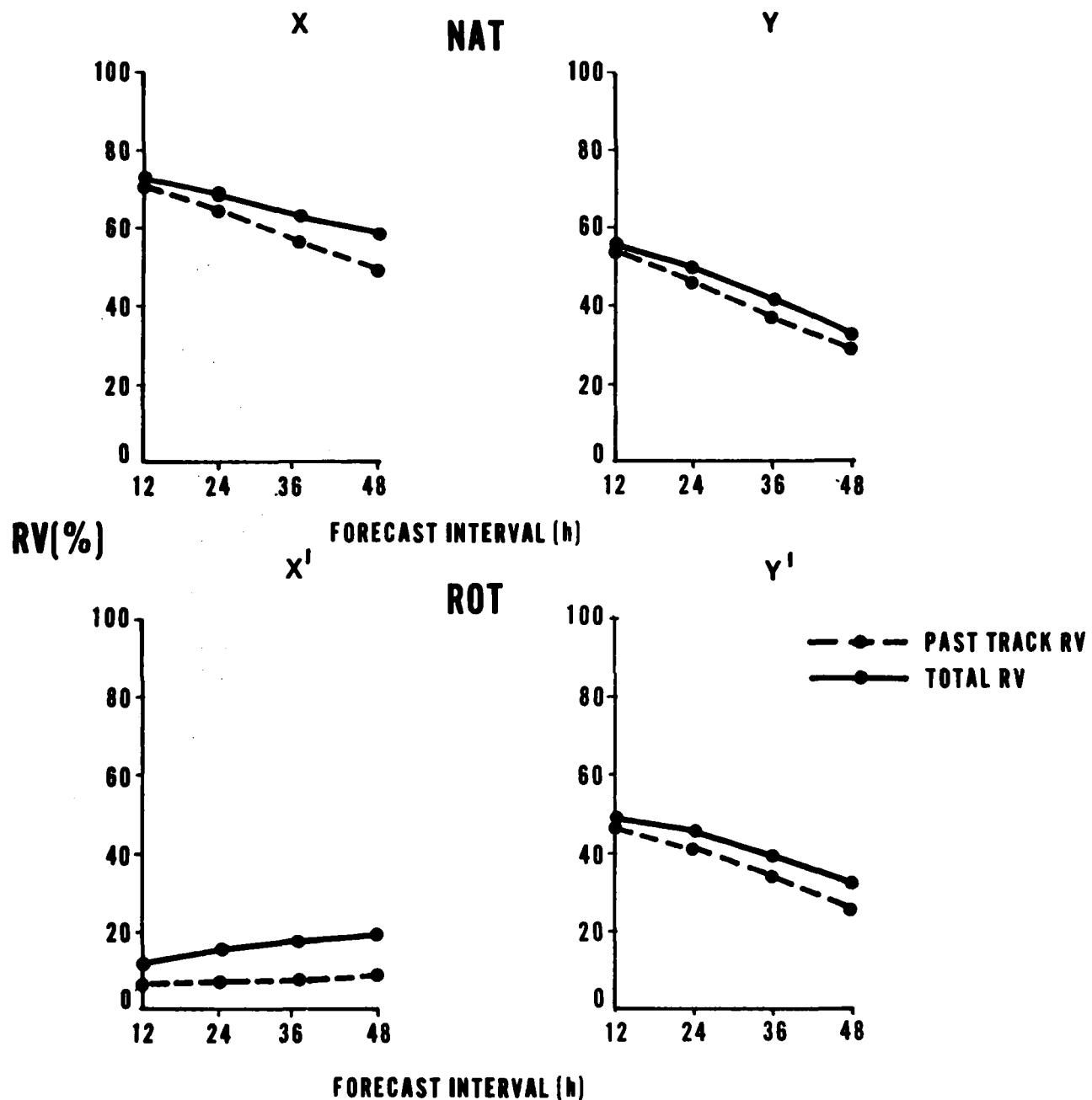
Figure 12. The reduction of variance (RV) in both component directions for the NAT and ROT coordinate systems, for the COM forecast equations.

2.4 Global Band Regression Equation Forecast Errors

Mean forecast errors for the global band equations are shown in Table 8. The independent data were 1982/83 Southern Hemisphere storm in the area 0-180°E and forecast by JTWC.

Table 8. Mean vector errors (km) and standard deviations (km) of global band field regression equations.

Mean Vector Error:

Forecast Interval	Method	Dependent Data	Number	Independent Data	Number
	COMNAT/COMROT	85/84	2145	120/124	95
12	GEONAT/GEONAT	102/106	2145	138/140	95
	STRNAT/STRNAT	87/88	2145	122/125	95
	COMNAT/COMROT	183/185	1943	220/240	79
24	GEONAT/GEOROT	248/256	1943	273/280	79
	STRNAT/STRROT	189/207	1943	225/264	79
	COMNAT/COMROT	286/297	1748	313/351	70
36	GEONAT/GEOROT	387/423	1748	390/446	70
	STRNAT/STRROT	294/312	1748	310/357	70
	COMNAT/COMROT	391/412	1563	398/455	62
48	GEONAT/GEOROT	560/633	1563	470/633	62
	STRNAT/STRROT	411/439	1563	414/470	62

Standard Deviations:

	Method	Dependent Data	Number	Independent Data	Number
	COMNAT/COMROT	67/68	2145	87/87	95
12	GEONAT/GEOROT	101/107	2145	119/120	95
	STRNAT/STRROT	69/69	2145	86/85	95
	COMNAT/COMROT	125/127	1943	149/153	79
24	GEONAT/GEOROT	256/294	1943	242/238	79
	STRNAT/STRROT	130/144	1943	140/161	79
	COMNAT/COMROT	178/183	1748	192/218	70
36	GEONAT/GEOROT	409/489	1748	323/476	70
	STRNAT/STRROT	183/193	1748	194/227	70
	COMNAT/COMROT	233/240	1563	227/245	62
48	GEONAT/GEOROT	625/801	1563	399/748	62
	STRNAT/STRROT	242/258	1563	238/279	62

Unlike the dependent data, the initial locations were operational fixes as judged by JTWC. The independent forecasts were also verified against these operational fixes. Unfortunately some cases could not be treated because of the lack of global band data south of 40°S.

In both the dependent and independent data sets, the lowest errors were achieved with the COMNAT equations. With the best-track dependent data, the percentage difference between the COMNAT and COMROT errors were -1.3% at 12h, 1.1% at 24h, 3.7% at 36h and 3.2% at 48h. With the independent data, however, the percentage differences were 3.3% at 12h, 9.1% at 24h, 12.1% at 36h and 14.3% at 48h. The α values were 37% at 12h, 20% at 24h, 14% at 36h and 9% at 48h. Thus the rotated coordinate system did not produce any statistically significant impact on the dependent "best-track" errors, and resulted in substantially worse errors than the NAT system with the operational-track independent test data.

This was probably due to initial position errors disturbing the subgrid orientation and thus the value of the synoptic predictors. This effect would be greater in the ROT system, since the initial position errors would become magnified away from the storm's center. The past track predictors would also be affected to a greater extent in the ROT system. The STR stratification was not as effective as the COM results; this was still encouraging. The STR developmental samples were, by necessity, smaller than those of the COM equations. Because of the poor GEO equation results, however, it was apparent that

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stratification procedures tended not to produce any real improvement. Reduction in the number of independent cases, due to serial correlation effects, was undoubtedly the reason for such failures, especially when the sample sizes were already decreased in the development of the stratified equations.

Compared with the previous Australian CREG approach discussed in Part 1, the percentage difference with the COMNAT results were 0.8% at 12h, 6.3% at 24h, 6.4% at 36h and 0.0% at 48h. These are not significant differences, although averaged over all the forecast intervals it did indicate a slight favoring of the CREG approach. As the synoptic component RV in the global band equations was also very similar to those presented by Keenan (1982) for the CREG type equations, it must be concluded that use of these synoptic wind fields produced no real impact on the forecasting accuracy.

2.5. Summary and Conclusions, Part 2

Equations developed with the FNOC global band data indicated that the use of track oriented grid coordinate systems did not appear viable in an operational mode. In addition use of the wind field instead of mass field predictors, usually employed in such equations, produced a slightly negative impact (i.e., an error increase). The difference was not significant; and thus, the type of synoptic grid-point data used to represent the synoptic forcing did not appear to be an important factor in limiting the performance of the Southern Hemisphere statistical-synoptic approaches. This result was probably a consequence of fields being represented poorly in the data void regions of the Southern Hemisphere.

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